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ORGANIC GEOCHEMISTRY OF ORDOVICIAN COLLINGWOOD OIL SHALES ON MANITOULIN, COCKBURN, DRUMMOND AND ST. JOSEPH ISLANDS SOUTHERN ONTARIO

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ABSTRACT

Cores from three recent Ontario Geological Survey and four earlier industry coreholes of Collingwood oil shale beds on St. Joseph, Drummond, Cockburn and Manitoulin Islands were sampled and analyzed by Rock-Eval pyrolysis to gain a broader regional knowledge of the kerogen type and thermal maturation history of that deposit. This was done in anticipation that better understanding will then be possible for other Ordovician organic-rich beds of northern Canada which may be important source rocks for frontier off-shore petroleum accumulations.

Kerogen has been determined to be entirely Type II marine which has been increasingly matured west to east across southern Ontario. Maturation changes are reflected in reduced Hydrogen Indices, increased Tmax values, decreasing yield potential and decreasing residual total organic carbon content. The changing relationships of these parameters with increasing maturation in this deposit will be an excellent guide to the evaluation of other similar oil shales.

INTRODUCTION

Oil shales of the Upper Ordovician Collingwood Member of the Lindsay Formation (Russell and Telford, 1983) are of significant geochemical interest because of the initially reported variations in levels of thermal maturation and possible admixed kerogen Types I and II (Barker et al., 1983) along its outcrop belt from Manitoulin Island to Whitby (Fig. 1). The conclusions of Barker et al. (1983) were based on data from 20 holes cored by the Ontario Geological Survey to determine the economic potential of the Collingwood beds as an oil source. Further interpretation of those cores was made by Macauley and Snowdon (1984) who considered the kerogen to be entirely Type II with hydrocarbon recoveries related to variable maturation levels. Sacheli (1985) has postulated zones of Type I and of Type II kerogens to explain some of the range of petroleum recoveries, but also considered hydrocarbon migration within the beds as a possible explanation.

Several cores have been more recently cut by the Ontario Geological Survey on St. Joseph Island, Cockburn Island, Manitoulin Island and the Bruce Peninsula (Fig. 1): several industry cores are also available from St. Joseph Island and from Drummond Island in the United States. These additional cores were sampled to expand the data base and geographic area for interpretation of the depositional and thermal histories of this oil shale interval. A more complete understanding of kerogen type

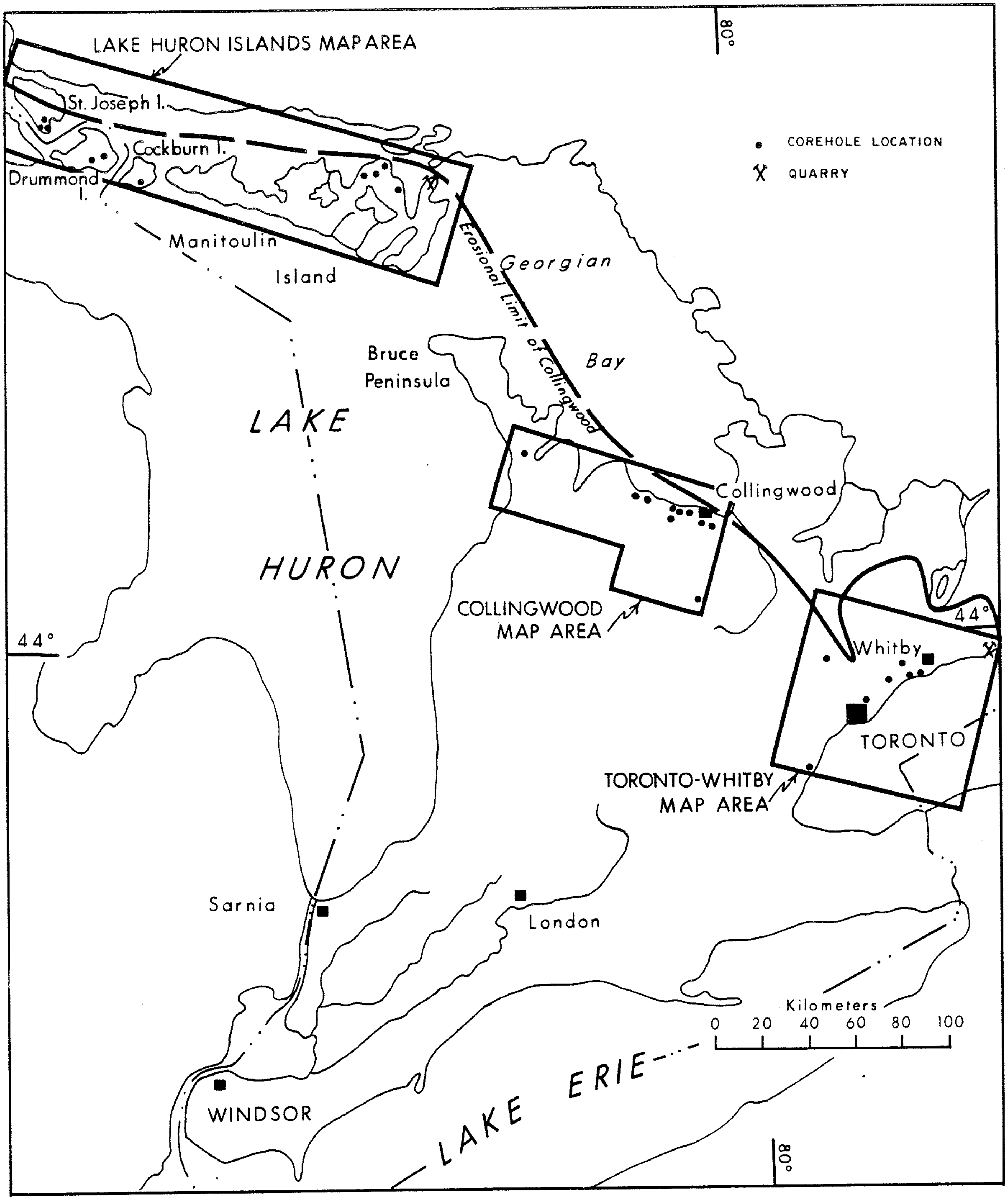


Figure 1: Regional corehole location map.

and the effects of thermal maturation in this area can be applied to similar kerogens known from Ordovician beds in northern Canada on Southampton Island (Macauley, 1984) and Baffin and Akpatok Islands (Macauley, in prep.).

To provide a common base for the interpretations, Rock-Eval data have been compiled in Appendix A from all previous sources (Macauley and Snowdon, 1984; Sacheli, 1985; Snowdon, 1984) as well as the more recent analyses of this study. All of the above analyses have been conducted at the Institute of Sedimentary and Petroleum Geology (ISPG), Calgary.

Sampling

An attempt was made by the writer to sample both on the basis of a regular interval and on the inclusion of all apparent lithologic types. All such samples were selected at specific depths. Some data reported from other publications were based on averaged intervals, generally one metre or less in thickness, designed to accomodate the large sample size required by Fischer Assay analyses. As reported and specifically noted in Appendix A, these samples are assigned a depth medial in the interval: the reader can acquire the complete data range from the referenced source. Insufficient Rock-Eval analyses were available from the earlier work to justify interpretations at several locations, especially in the Collingwood area, but this has been in part been remedied here.

Both metric and Imperial depth measurements have been utilized during the coring operations. Because all the Ontario Geological Survey cores are measured in metric, all data have been converted to this system.

Analytical Technique

Samples were processed on a Rock-Eval analyzer at ISPG, Calgary, under the direction of Dr. L. R. Snowdon, using a standard program. The S1 peak was obtained at 300°C: the S2 was measured during heating at 25°C/min. and collected to a temperature of 600°C. The S3 peak was collected to a temperature of 390°C.

Total organic carbon (TOC) for the current samples was determined by after-burning all residual organic carbon in the analyzer. In order to ensure uniform results and that all the organic carbon was burned, samples were ground to a particle size of approximately 150 microns. For those samples incorporated from prior publications, TOC was determined in Leco WR12 carbon analyzers at either ISPG or the University of Waterloo after samples had been pulverized to 150 microns and treated in both cold and hot 6N hydrochloric acid to remove mineral carbon (Macauley et al., 1985).

Several standard procedures have been employed in the past for the interpretation of Rock-Eval data. Of these, the Hydrogen Index/Oxygen Index (HI/OI) cross-plot has been the most useful in the determination of both kerogen type and thermal maturation level, although kerogen type becomes less distinct as the maturation level increases. To assist further in the understanding of the data, several other cross-plots have been prepared: HI/TOC, HI/Tmax and Tmax/TOC. The standard TOC/Petroleum Potential plot to define yield potential has also been prepared. Based on the above, in conjunction with Production Index (PI) values, an interpretation of regional kerogen distribution and thermal maturation is here presented.

STRATIGRAPHY

Collingwood beds form the upper member of the Lindsay Formation (Russell and Telford, 1983), whereby organic-rich Collingwood carbonate overlies a thick carbonate sequence of the Lindsay Formation and is in turn overlain by non-organic shales of the Blue Mountain Formation. The Collingwood is included within the Lindsay Formation because of the common carbonate mineralogy and also because of the distribution of thin oil shale lenses within a carbonate section which is included as a lower part of the Collingwood Member. A review of prior paleontological studies (Macauley, 1984, p. 11) indicated the black shales of the Eastview Formation in the Ottawa area (Fig. 2), approximately 200 km to the east, to be the equivalent of uppermost Lindsay carbonates. Organic-rich beds are present locally in the Whitby area as the Rouge River Member (Fig. 2) within the overlying Blue Mountain shales (Russell and Telford, 1983).

The Collingwood/Lindsay carbonate contact has been described and discussed in some detail by Churcher (1985) who had difficulty reconciling apparently conformable, gradational boundaries with obviously eroded uppermost carbonate surfaces at other nearby locations. Similarly, the Collingwood/Blue Mountain contact can also be locally gradational, locally sharp but conformable, and locally erosional (Harris, 1984). Collingwood beds pinch out southward (Fig. 2), occurring as thin sporadic outliers along the southern distributional limit (Churcher, 1985). Detrital erosional zones are part of the normal depositional process in all shallow water sediments and also in some deeper water deposits. Nowhere is deposition always continuous: each break may represent only a local disturbance with the entire sedimentary record represented over a broader area. Deposition is considered to have been uninterrupted from Lindsay carbonate through the Collingwood organic beds into the Blue Mountain shale sequence.

Collingwood beds are typical of marine, widespread, shallow water, organic-rich deposits, commonly carbonates, which follow carbonate sedimentation and which precede non-organic shale intervals. Numerous examples of such sequences are known in the Devonian of Canada, including the Middle Devonian Marcellus Formation of southern Ontario (Goodarzi and Macauley, in prep.), the numerous dark shales included within the Horn River of the Northwest Territories (Williams, 1984), the Canol Formation

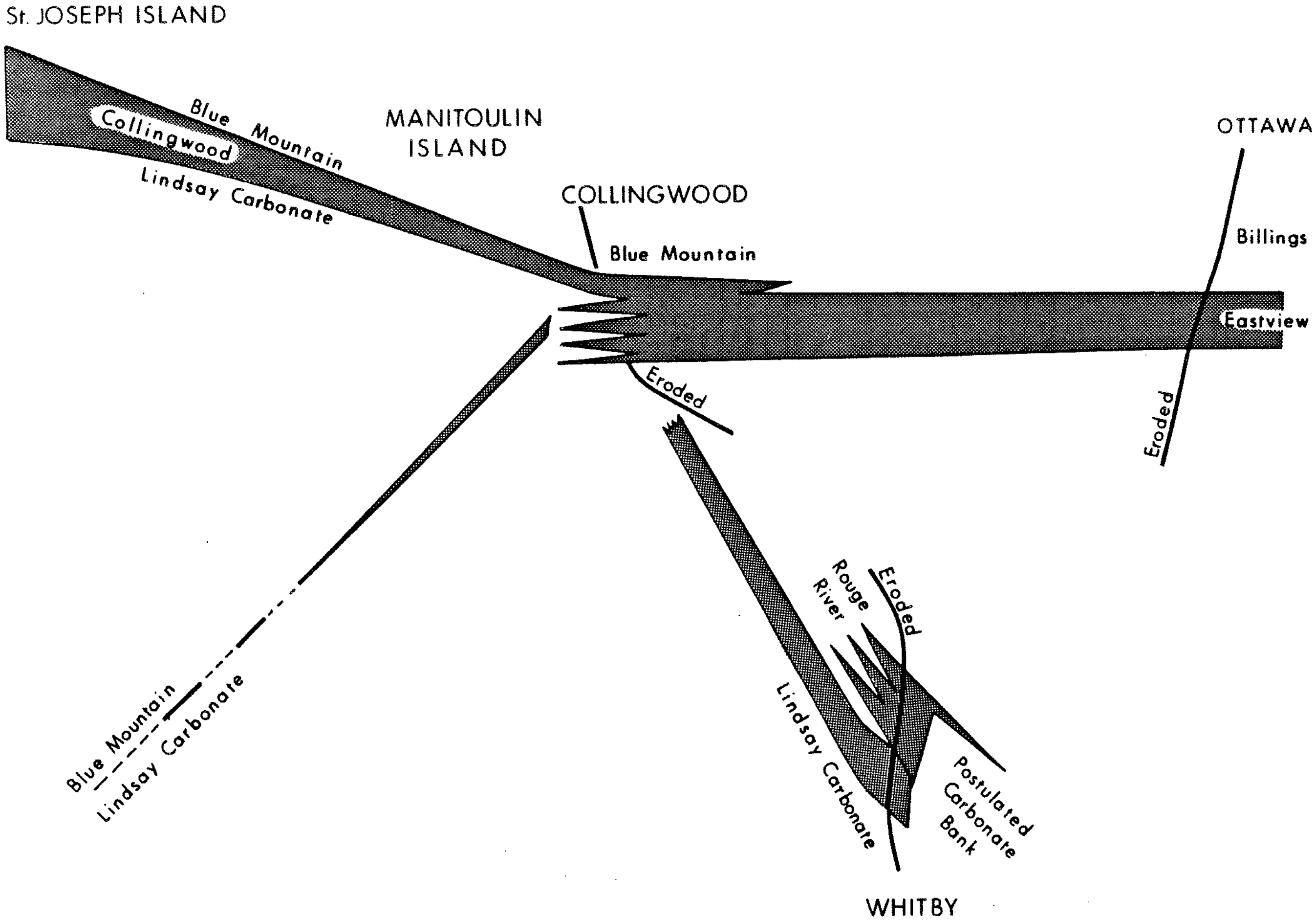


Figure 3: Diagrammatic representation of the relationship of the Collingwood oil shales to overlying and underlying beds.

The section is considered to be a complete, normal depositional sequence, uninterrupted by tectonism, uplift and/or erosion on any significant scale. The interbedding of oil shales within the Lindsay carbonate in the Collingwood area equates to the Eastview interval of the Ottawa area (Fig. 2), indicating proximity to a carbonate front now eroded northeastward of the Collingwood boreholes. Similarly, the organic-rich interbeds of the Rouge River Member in the Whitby area may indicate that a younger biogenic bank once existed southeast(?) of this area. The local thin outliers and irregular southern limit of the Collingwood were controlled by the drainage system within the submerged areas between the inter-tidal carbonate bank deposits. Some degree of regional depositional thickening is indicated northwestward to the islands of Lake Huron (Fig. 2): this may represent a minor increase in the rate of downwarp, a better sediment supply, and/or a less obvious facies relationship to the underlying carbonate.

DISTRIBUTION

Although by definition the Collingwood Member comprises all organic-rich intervals to the base of the lowest oil shale bed, and thus includes considerable non-organic carbonate, the unit is herein restricted to the upper continuous organic-rich section uninterrupted by non-organic carbonates. On the basis of oil shale development potential, the percentage of oil shale within the lower dominant carbonate section is too low to be economically significant. In this aspect, values here will differ in part from those of Churcher (1985), especially in the Collingwood area, as Churcher's isopachous values encompass the entire member.

Generalized thickness values indicate the thinnest section (<2m) to be in the Collingwood area, overlying the Algonquin Arch, with thickening to both the northwest and southeast (Fig. 2). Maximum thicknesses (almost 11m) were encountered at the 3 coreholes on St. Joseph Island. Thickness data for all locations, and also for coreholes where Rock-Eval data are not available, are included in Table I.

A more comprehensive presentation of the distribution is illustrated in Fig. 4, where isopachous contours are included for the Lake Huron islands and for the Toronto-Whitby area. For both areas, the reflection of thickening off the Algonquin Arch can be recognized.

Thickness distribution is regular with a notable exception at OGS 83-5 on Manitoulin Island. In addition to the mapped 2.30m of oil shale, a further 3.07m is described as petroliferous at the base of the Blue Mountain shale section and the downhole logs indicate possible organic content; however, the zone is not reported as characteristic oil shale lithology (Johnson et al., 1985). This may result from a minor facies change in the upper part of the Collingwood interval. This thinner oil shale at this locale could also result from non-deposition of part of the interval over a carbonate mound. A review of this core is warranted as 5.37m may be a more accurate value and the anomaly would thus be removed.

GEOCHEMISTRY

An initial inspection of the Rock-Eval data (Appendix A) shows that the various parameters are consistent within small ranges for the St. Joseph and Drummond Island coreholes. Those on Cockburn Island have a slightly wider range of values, with the range increasing across the Manitoulin Island locations to the Collingwood area. There, the widest range of values was obtained for several of the key indicators, especially the Hydrogen Index, which has many lower values. Coreholes in the Whitby area consistently indicated the poorest Hydrogen Indices and hydrocarbon recovery potentials. Thus a distinct west to east change of parameter values was easily identified. Data were then arranged in a west to east order for presentation (Appendix A) and interpretation.

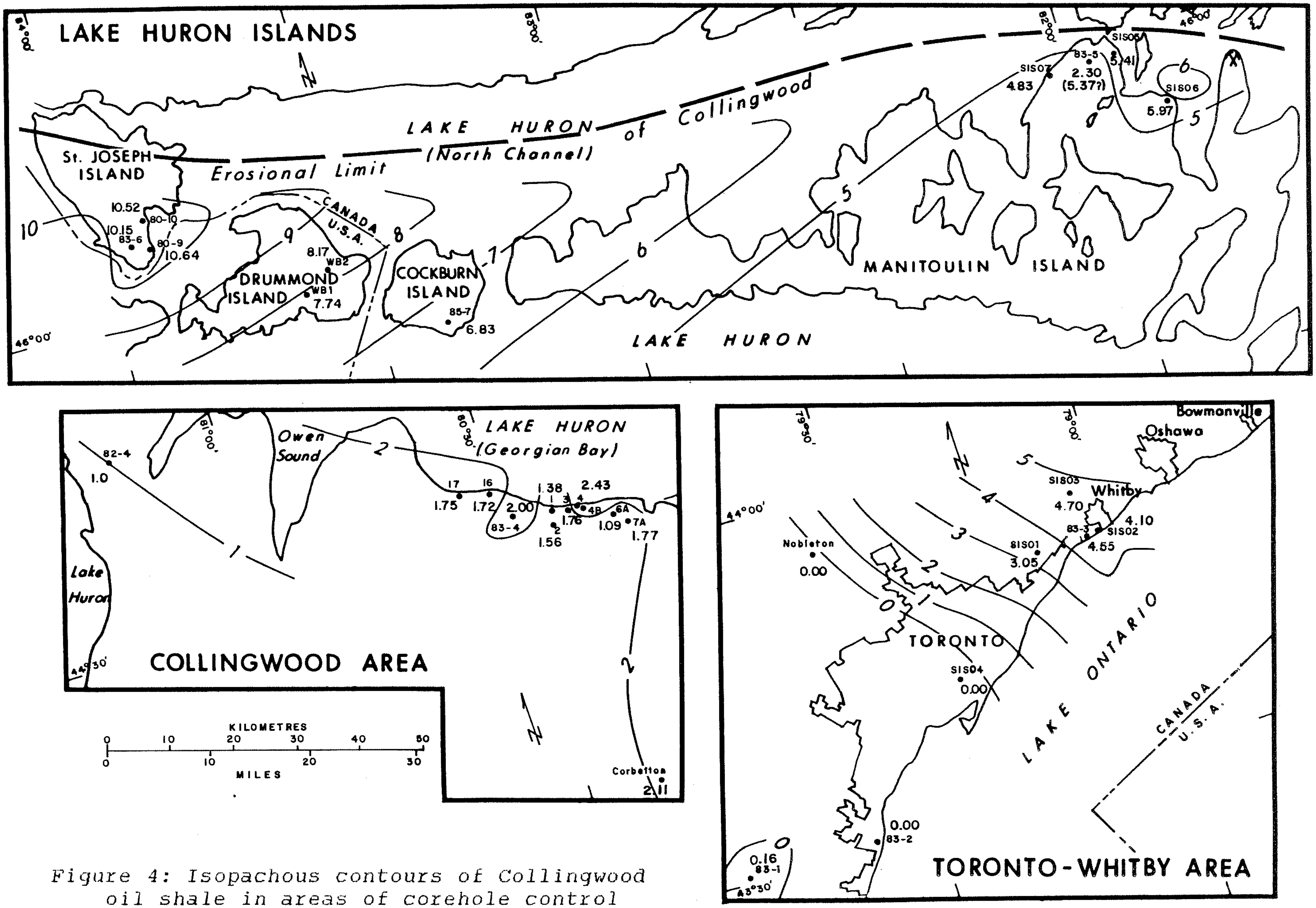


Figure 4: Isopachous contours of Collingwood oil shale in areas of corehole control

Cross-plots were next made of the HI/OI relationship (Fig. 5). Although the averaging of geochemical data could be deceptive, the distinct downward shift that can be recognized following west to east across these plots indicates that an averaged Hydrogen Index at each location will define the relative change across the area. All key parameters were then averaged to assist interpretation (Table I).

Classification and Maturation

Three distinct cross-plot patterns can be recognized for the Hydrogen and Oxygen indices. The coreholes on St. Joseph and Drummond islands plot consistently within a small area in the 500-600 HI range (Figs. 5a-e). Tmax values are near 430°C at four of the five locations, indicating thermal immaturity in this area. Coreholes on Manitoulin Island and in the Collingwood area (Figs. 5g-k) exhibit a Hydrogen Index range of 200 to 700, with Tmax values from 438 to 440°C. These are indicative of marginal to low thermal maturity. The last group, where HI values are consistently below 400 (Fig. 5l), occurs in the Whitby area, with Tmax values in the range 441-444°C, indicating low to moderate maturity within the oil shale window. The Collingwood oil shales intersected in OGS 85-7 (Fig. 5f), on Cockburn Island, appear to be within the marginal to low maturity range.

Because of the much lower bonding strength of oxygen to carbon relative to C-C and C-H bonds, oxygen is theoretically lost early in the thermal maturation cycle; however, OI values remain consistently in the range 10-30, which may indicate that the excess oxygen of the kerogen was removed well below the initial petroleum generation level or that the oxygen is intricately contained within the kerogen macerals. Samples from surface exposures and quarries are devoid of oxygen, a possible surface weathering effect.

The Production Indices (Table I) are essentially all less than 0.1 for the immature to marginal or low maturity areas from Collingwood westward, indicating that bitumen has been the generated hydrocarbon with minimal light petroleum product. OGS 85-7, on Cockburn Island, has a higher average PI (0.115) than coreholes to either the east or west. PI values in the Whitby area are near 0.2, indicating considerable generation of light hydrocarbons. Bitumen is here used to define the early generated heavy ashphaltic hydrocarbons which pyrolyze within the S2 peak. In contrast, Sacheli (1985) has used bitumen to define the S1 peak product, and his bitumen/kerogen ratio correlates to the Production Index herein.

The immature beds classify the kerogen as Type II even though the Oxygen content may be lower than expected. Sacheli (1985) considered the higher HI values in the Manitoulin Island and Collingwood areas to be possibly indicative of a Type I kerogen content although he did so with strong reservations. As

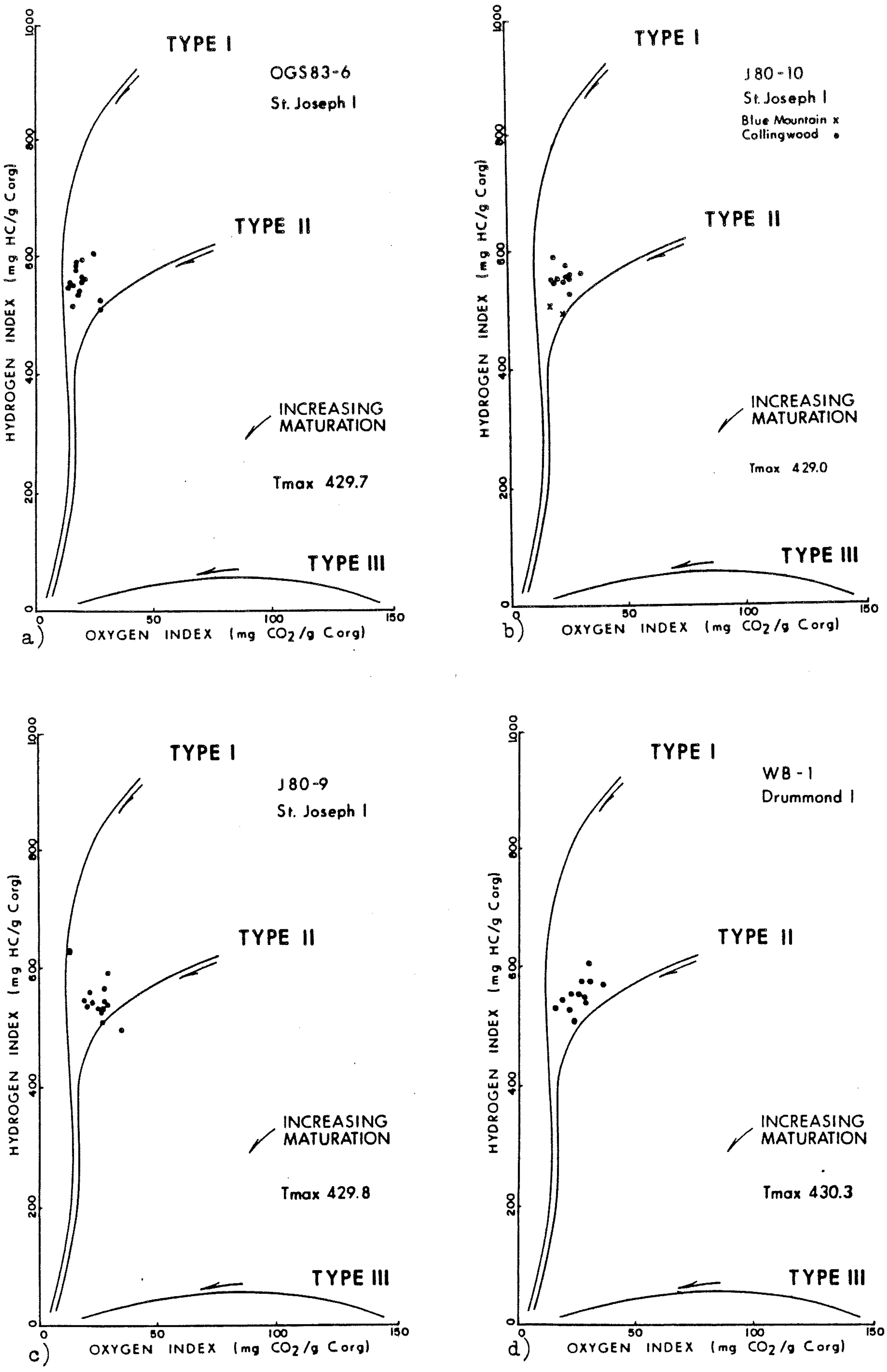


Figure 5: Hydrogen Index versus Oxygen Index

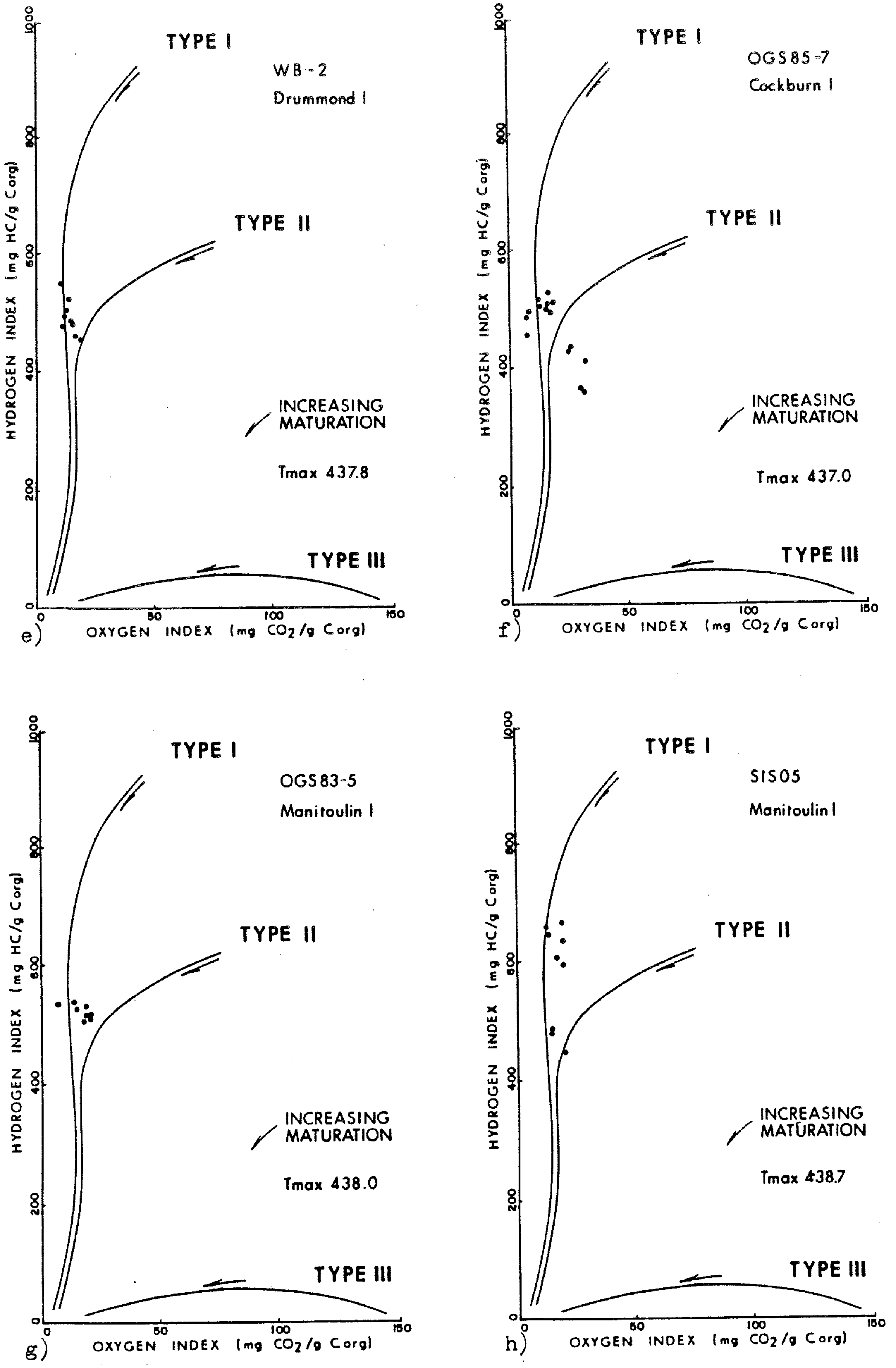


Figure 5: Hydrogen Index versus Oxygen Index (continued).

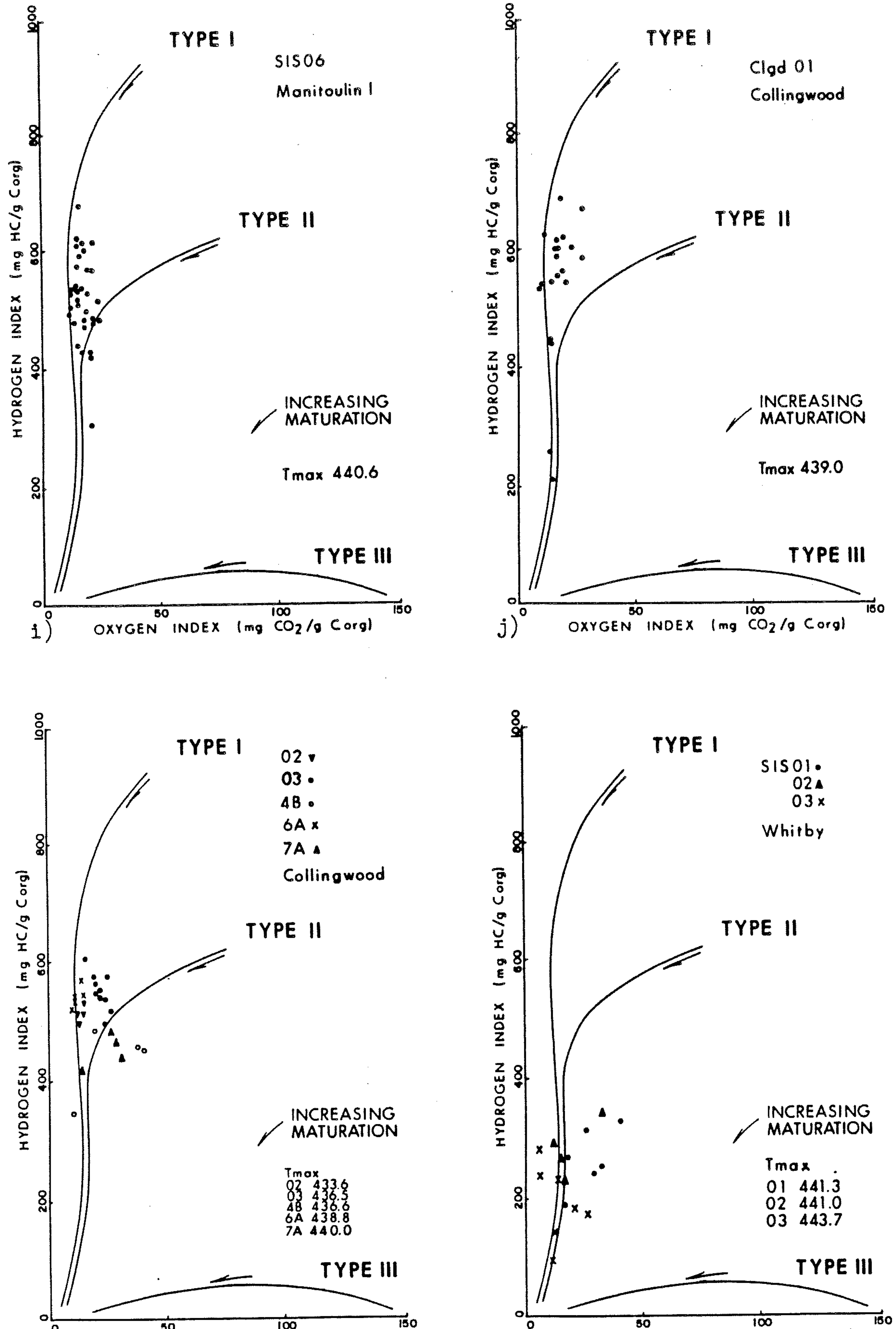


Figure 5: Hydrogen Index versus Oxygen Index (continued).

Location	Thickness m	TOC Wt%	Tmax °C	HI	PI	Yield Ratio kg/t/%TOC
St.Joseph I.						
OGS 83-6	10.15	5.47	429.7	558	.066	5.97
J80-10	10.52	5.56	429.0	549	.075	5.91
J80-9	10.64	4.85	429.8	544	.081	5.91
Drummond I.						
WB-1	7.74	5.66	430.3	551	.079	5.95
WB-2	8.17	5.56	437.8	492	.095	5.45
Cockburn I.						
OGS 85-7	6.83	5.00	437.0	464	.115	5.23
Manitoulin I.						
SIS 07	4.83	5.88				
OGS 83-5	2.30	4.56	438.0	526	.073	5.56
SIS 05	5.41	5.80	438.7	572	.072	6.18
SIS 06	5.97	5.75	440.6	520	.059	5.56
Collingwood area						
OGS 82-4	1.00	6.79				
Clgd 17	1.75					
Clgd 16	1.72	5.65				
OGS 83-4	2.10					
Clgd 01	1.88	4.78	439.0	541	.073	5.86
Clgd 02	1.56	6.43	433.6	513	.092	5.56
Clgd 03	1.76	7.24	436.5	432	.065	4.64
Clgd 4B	2.43	6.04	436.6	561	.067	6.04
Clgd 6A	1.69	5.91	438.8	544	.080	5.94
Clgd 7A	1.77	6.11	440.0	406	.057	4.33
Corbetton	2.11	4.09				
Whitby area						
OGS 83-1	0.16					
OGS 83-2	0.00					
Nobleton	0.00					
SIS 04	0.00					
SIS 01	3.35	4.35	441.3	229	.242	3.44
OGS 83-3	4.55					
SIS 03	4.70	4.11	443.7	195	.231	2.38
SIS 02	4.00	4.35	441.0	284	.168	4.08
Ottawa area						
SIS 10		2.56	466	26	.57	0.57

Table I: Averaged Rock-Eval geochemical data, Collingwood oil shale, arranged by location west to east

the Hydrogen Indices do not commonly reach the 700-1000 range normally encountered in immature to low maturity Type I deposits (Macauley et al., 1986), the presence of admixed Type I kerogen should be discounted.

Sacheli (1985) also proposed that the range of HI values in these areas could be attributed to early movement of the bitumen (S1 peak) to create richer and poorer intervals. Lithologically, the oil shale beds grade from massive (several cm) to laminated. The more massive beds dominate to the east in the Whitby area and to the west on St. Joseph and Drummond Islands in the thicker sections. Laminated beds are more prevalent in the upper part of the section and increase noticeably in the Collingwood and Manitoulin Island cores. In the Collingwood area, where the total section is thinnest, some of the upper beds become papery laminated and fissile. The movement of bitumen (S2 peak) and light petroleum products (S1 peak) in beds of this nature is easily accepted. Sacheli's concept of early bitumen migration to explain both the raising and lowering of Hydrogen Indices is a preferred explanation if bitumen is confined to S2 peak hydrocarbons. There are only a few PI values that deviate greatly from a minimum indicated range at each location. Tmax variations may then relate to the relative heavy bitumen/kerogen content in a specific sample. Whether or not the early bitumen movement would similarly occur in the more massive sections is difficult to determine. Once the major part of the kerogen had been converted to bitumen and the generation of light petroleum had commenced, as in the Whitby area, Hydrogen Indices would again cluster because of the greater uniformity of the material being pyrolyzed.

Recovery Potential

Recovery potential is governed by two factors: TOC content and the yield ratio (kg/t/%TOC). The product of these two factors is defined as the Petroleum Potential (Appendix A).

TOC: At first glance, TOC distribution appears to be relatively uniform except for the Whitby area (Table I). Sampling irregularity may distort any analysis of TOC distribution, as the more laminated beds have higher organic carbon content than the more massive intervals. Although a possible imbalance in sampling, especially in the thinner sections and at those locations with only a few analyses, prevents a conclusive interpretation of TOC distribution, some observations may be pertinent. To the west on St. Joseph and Drummond Islands, average TOC may be anticipated at approximately 5.5%, on Manitoulin Island at 5.8%, and over 6% in the Collingwood area. From a visual inspection of the cores, without detailed study, this eastward increase of average TOC can be attributed to an increasing ratio of laminated/massive lithotypes. At present, this is merely an observation.

An average 5% TOC at OGS 85-7 on Cockburn Island is less than anticipated from the projected regional distribution. Lower TOC, reduced Hydrogen Indices and higher than expected PI values indicate this location to be more mature than coreholes on the islands to the west, on Manitoulin Island and in the Collingwood area to the east. An increased maturation level can account for the reduced averaged TOC.

At 4.3% in the Whitby area, TOC is significantly reduced, but thermal maturation levels are sufficiently higher that up to 2% of initial organic carbon has undoubtedly been converted to hydrocarbons which no longer reflect in the TOC values. The oil shales, when deposited in the Whitby area, probably contained organic carbon comparable to that of the other areas.

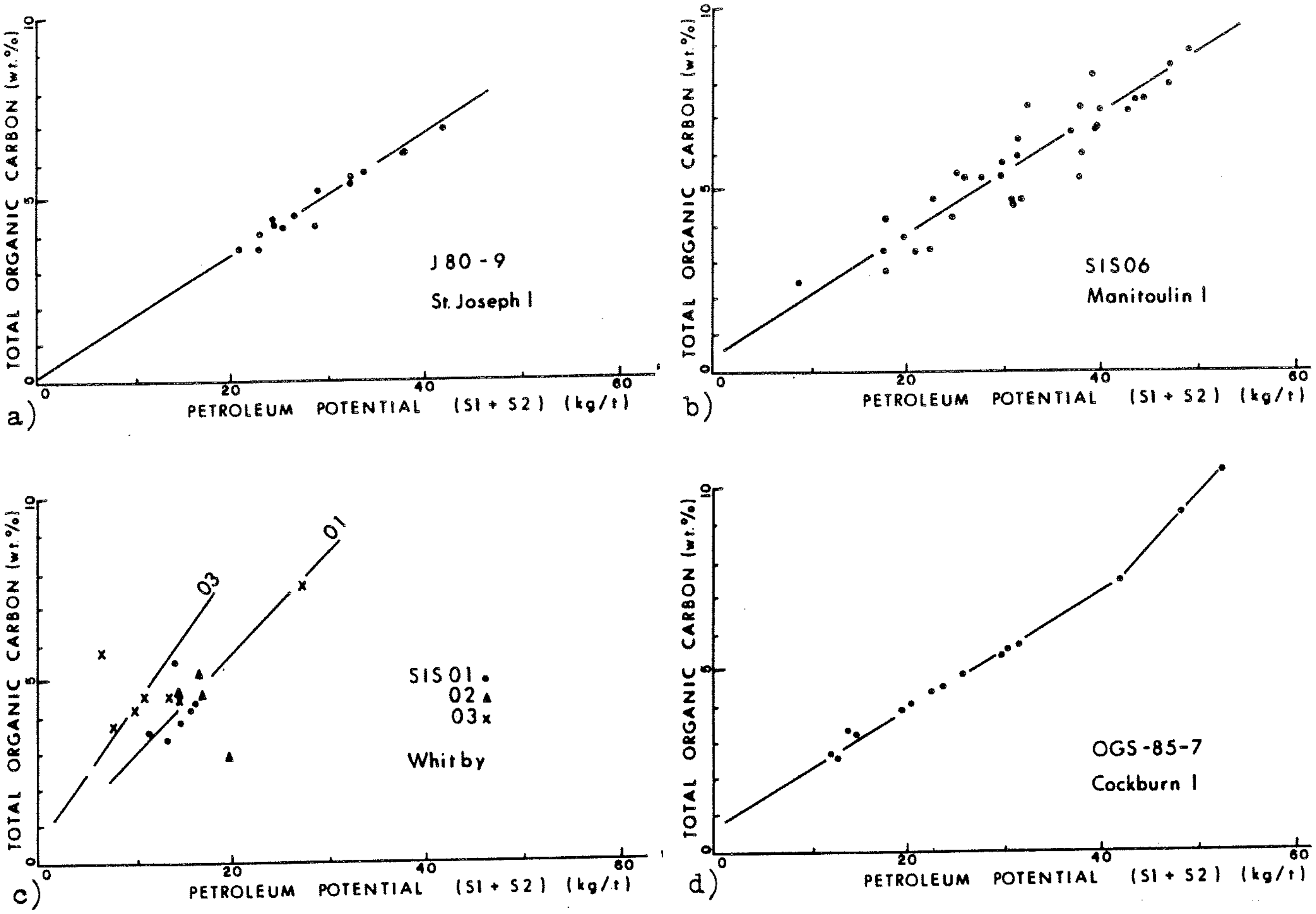


Figure 6: Total organic carbon versus petroleum potential.

<u>Yield Ratio</u>: Cross-plots of the Petroleum Potential (S1+S2) against TOC were prepared for all coreholes. Similar to the HI/OI plots, three distinct relationships were evident for the same three areas. A typical plot has been selected to illustrate each relationship. Values from immature beds plot in a straight line relationship, essentially passing through the origin, but notably with most of the data points lying almost directly on the averaged line plot (Fig. 6a). Commensurate with the increasing HI variability, the spread of the data points from the average line increases at the low maturity locations on Manitoulin Island and in the Collingwood area (Fig. 6b). The slope of the lines for the two areas remain almost identical, a characteristic expected as minimum light hydrocarbons have been generated in both areas. In the Whitby area of moderate maturation, the yield ratios are considerably reduced (Table I) with a significant change in line slope (Fig. 6c). Because of the increased movement and probable expulsion of some light hydrocarbons, the data points become more widespread and averaged lines are difficult to project. Yield ratio lines for the Manitoulin Island and Collingwood areas project slightly above the origin and this is emphasized even further for the Whitby area, indicating an increasing amount of organic carbon that is now inert as regards petroleum generation.

OGS 85-7 has characteristics of both the immature and low maturity areas (Fig. 6d). The values fall along a virtual straight line but indicate approximately 1% inert carbon. Two high carbon samples yield at a lower rate than is projected from the other data. Greater maturity is indicated by the upper eight samples from this corehole (Appendix A): the samples below this point are much closer in character to those of the coreholes to the east. From brief descriptive notes made during sampling, the upper section darkens downward to a wavy interface at 325.18m, below which normal Collingwood character is encountered. One can speculate that a similar section may be present in the "petroliferous" zone described (Johnson et al., 1985) above the anomalously thin interval analyzed at OGS 83-5 on Manitoulin Island.

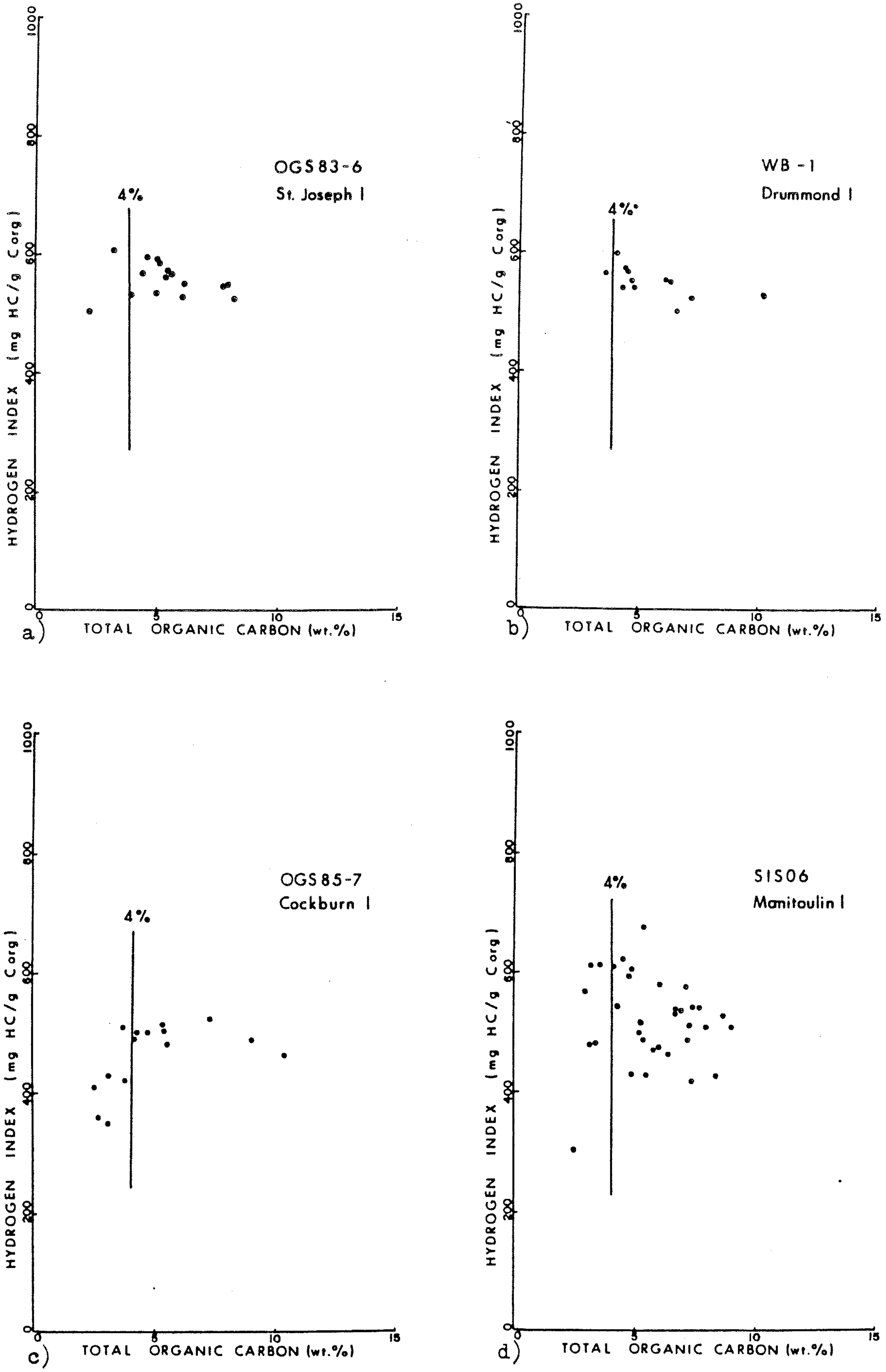
Mineral matrix effect is a difficult factor to evaluate. Whether or not there is a minimum TOC content, below which generated products cannot escape, is significant to economic development potential, as the elimination of all low grade ore from the retorting process is not possible. A study of hydrocarbon recoveries from Carboniferous Type I deposits in Newfoundland (Macauley, in prep.) indicate a distinct break in yield below the 4% TOC level: some low TOC values yielded little hydrocarbon whereas others were as prolific as the higher TOC beds. This was most evident in a HI/TOC cross-plot and lithologic variation of massive to laminated beds could in part explain this phenomenon. Several investigators, including J. F. Barker and the writer, have generally considered that yields from the Collingwood oil shales were reduced in beds which contained less than 4% TOC.

The Hydrogen Index was plotted against the TOC value for all locations. The two parameters are independent in thermally immature beds (Figs. 7a,b) with little indication of significantly reduced Hydrogen Indices in low TOC values for the St. Joseph and Drummond Island coreholes. Complete detail for low TOC samples can be ascertained from Appendix A.

OGS 85-7, on Cockburn Island, does indicate reduced HI values for TOC content below 4% (Fig. 7c). This location is anomalous to the maturation trend with lower TOC, a lower yield ratio and a higher PI (0.115) than would be expected, as previously outlined.

Both SIS 06 (Fig. 7d), on Manitoulin Island, and Clgd 01 (Fig. 7e) show a distribution in which most low TOC samples have normal HI with a few having reduced HI values. In the Whitby area, HI cannot be related to TOC variations (Fig. 7f).

Tmax-HI: For immature beds, Tmax generally increases as the Hydrogen Index increases (Fig. 8a). As maturation progresses, the Hydrogen Index increases more noticeably within a lesser range of increasing Tmax (Fig. 8b) or independently of specific Tmax values (Fig. 8c). As the moderate maturity range is entered, Tmax and HI become inversely proportional (Fig. 8d).



Hydrogen Index versus total organic carbon.

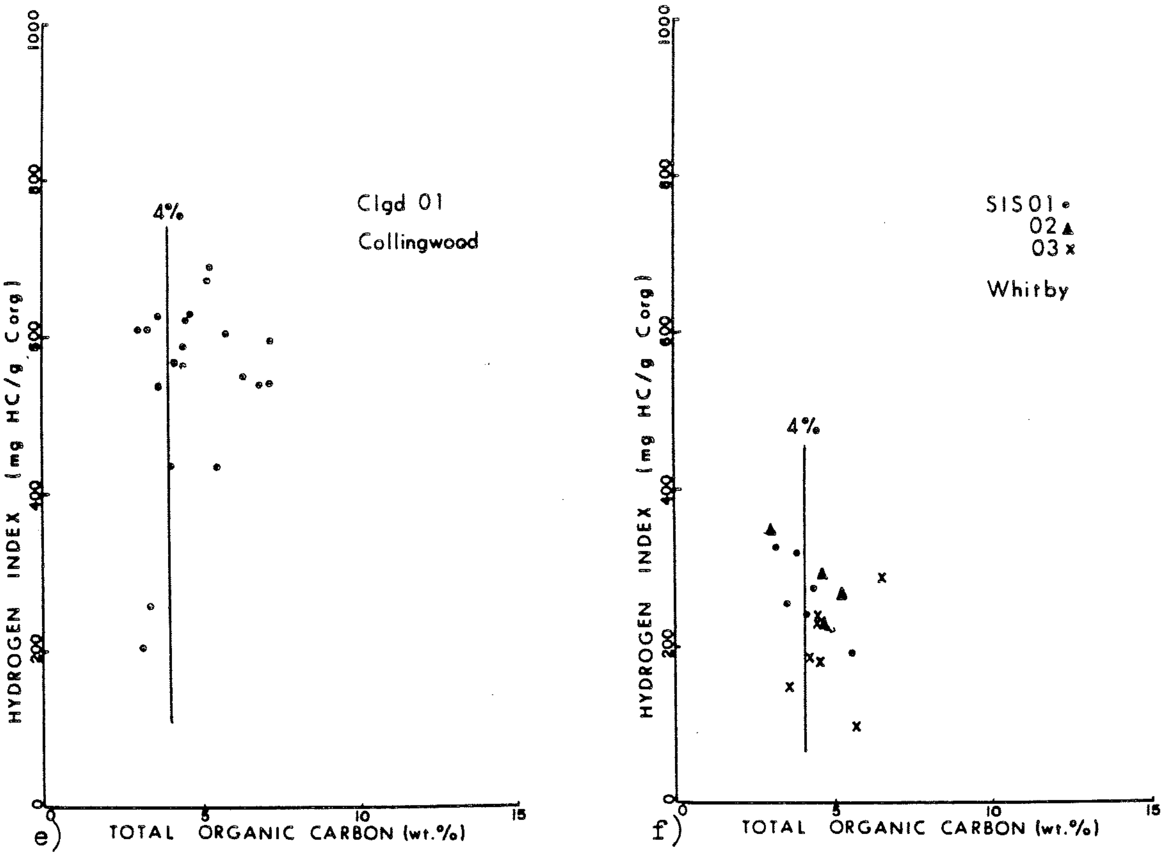


Figure 7: Hydrogen Index versus total organic carbon (continued).

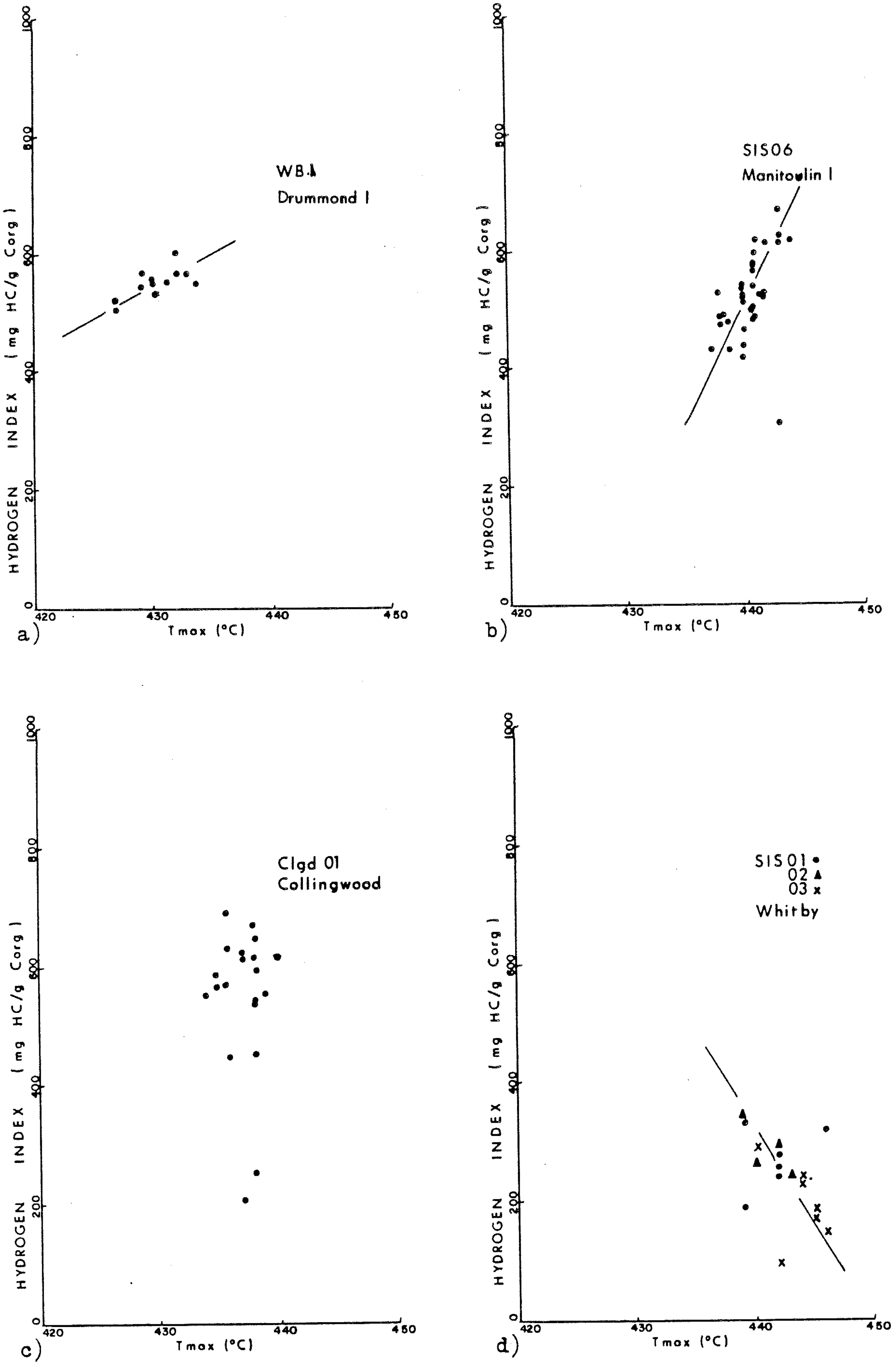
Commensurate with the above Tmax/HI and HI/TOC relationships, Tmax will in general decrease as TOC increases, which is probably a factor of the size and distribution of the kerogen macerals and the consequent ease in heating, breaking down and breaking away from the mineral matrix.

SUMMARY

Collingwood oil shales contain Type II kerogen and are typical of the shallow water, thin, areally widespread, marine, organic-rich beds which follow the cessation of blanket carbonate sedimentation and are succeeded by terrigenous clastic deposits.

Thermal maturation of the Collingwood oil shales increases eastward from immature in the St. Joseph - Drummond Island areas to marginal/low maturity on Manitoulin Island and in the Collingwood area, to low/moderate maturity in the Whitby-Toronto area and to overmature at Ottawa. A corehole on Cockburn Island is possibly more mature than expected from the regional pattern.

The varying thermal maturation is reflected in the HI/OI cross-plots wherein the Hydrogen Indices cluster uniformly where immature, become spread over a wider range where low to marginally mature and again cluster at a much lower average value at moderate maturity. These differences probably relate to the changing kerogen/bitumen ratios during the early conversion



Hydrogen Index versus Tmax.

of the kerogen to bitumen and prior to the dominant generation of light hydrocarbon products.

TOC content at the time of deposition was probably fairly constant in the range of 5.5 to 6% with the slightly greater values in the area of thinnest deposition near Collingwood. Lower TOC averages are now encountered where maturation has generated light hydrocarbons which do not form part of the measured TOC values. TOC values are not reduced by the conversion of kerogen to bitumen early in the maturation process.

Yield ratios for immature and marginal/low maturity beds, where light petroleum products have not been generated, remain fairly constant near 6 kg/t/%TOC, a value consistent with the Type II kerogen classification. Yield ratios then decrease as light hydrocarbons have been generated and in part expelled.

Tmax and HI are directly proportional for immature beds, become somewhat independent at marginal to low maturation levels as conversion to bitumen occurs, and are inversely related for low to moderate maturation where petroleum generation is taking place.

There does not appear to be a TOC content below which kerogen does not pyrolyze readily because of minimum content or mineral matrix effect: only a few samples indicate reduced Petroleum Potential for TOC below 4%.

Both OGS 85-7 on Cockburn Island, and OGS 83-5 on Manitoulin Island, warrant further investigation to assess apparent anomalous conditions at those locations.

Acknowledgements

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APPENDIX A

ROCK-EVAL ANALYTICAL DATA

COLLINGWOOD MEMBER

Southern Ontario

Published data incorporated herein (some apparently erroneous data selectively deleted):

* Macauley and Snowdon, 1984
# Snowdon, 1984
^ Sacheli, 1985

N.B. in depth column, m indicates median value of analyzed interval as reported by the authors

Depth m	TOC Wt%	Tmax °C	S1	S2 mg/g	S3	HI	OI	S1+S2 kg/t	PI	Ratio kg/t /%TOC
OGS 83-6, St. Joseph Island										
159.21	5.04	428	1.85	26.98	1.00	535	19	28.83	.06	5.72
159.44	6.14	430	2.26	32.28	1.14	525	18	34.54	.07	5.62
160.15	5.54	427	2.29	31.23	1.17	563	21	33.52	.07	6.05
160.58	5.35	431	2.07	29.81	1.10	557	20	31.86	.06	5.95
161.34	6.38	427	2.68	35.14	1.10	550	17	36.24	.07	5.68
161.85	7.89	430	3.37	43.04	1.24	545	15	46.41	.07	5.88
162.28	4.04	429	1.47	21.38	1.14	529	28	22.85	.06	5.65
163.28	8.39	430	3.58	43.25	1.40	515	16	46.83	.08	5.58
163.50	7.95	431	3.44	43.15	1.34	542	16	46.59	.07	5.86
164.28	4.84	431	1.85	28.72	0.96	593	19	30.57	.06	6.45
164.77	3.22	430	1.27	19.50	0.82	605	25	20.77	.06	6.45
165.43	5.15	430	1.83	29.94	0.98	581	18	31.77	.06	6.16
166.04	5.61	430	2.37	32.33	1.05	576	18	34.70	.07	6.18
166.98	5.02	430	2.01	29.66	0.94	590	18	31.67	.06	6.30
167.92	2.34	432	0.82	13.09	0.67	559	28	13.91	.06	5.94
168.40	4.63	429	1.95	26.26	0.91	567	19	28.21	.07	6.09
Rodgers Lacana J80-10, St. Joseph Island										
Blue Mountain										
69.95	3.31	429	1.10	16.24	0.78	490	23	17.34	.06	5.23
70.46	7.61	427	3.18	38.73	1.31	508	17	41.91	.08	5.50
Collingwood										
92.72	5.64	429	2.59	29.62	1.38	525	24	32.12	.08	5.69
93.84	5.25	428	2.36	28.97	1.34	551	25	31.33	.08	5.96
94.24	7.19	426	3.31	39.08	1.43	543	19	42.41	.08	5.89
95.73	3.65	431	1.72	21.34	0.91	584	24	23.06	.07	6.31
96.07	6.14	427	2.97	33.97	1.30	553	21	36.94	.08	6.01
96.95	4.35	428	1.95	24.27	1.08	557	24	26.20	.07	6.02
98.20	5.40	430	2.42	29.90	1.19	553	22	31.32	.07	5.80
99.06	5.61	431	2.39	33.46	1.14	596	20	35.85	.07	6.39
99.39	5.82	430	2.50	32.72	1.46	562	25	35.22	.07	6.05
100.94	8.38	430	4.01	46.25	1.56	551	18	50.26	.08	5.99
102.04	3.98	431	1.85	22.31	1.33	560	33	24.16	.08	6.07
Rodgers Lacana J80-9, St. Joseph Island										
138.83	5.68	430	2.88	29.76	1.44	523	25	32.64	.09	5.74
139.59	3.78	430	2.67	18.63	1.36	492	35	20.90	.13	5.52
140.51	7.00	430	3.66	38.07	1.39	543	19	41.73	.09	5.96
141.36	5.30	429	2.35	26.86	1.39	506	26	29.21	.08	5.51
142.20	5.77	428	2.68	30.88	1.44	535	24	33.56	.08	5.81
143.25	4.04	431	1.67	21.51	1.16	532	28	23.18	.07	5.73
144.25	4.10	432	1.84	23.36	1.13	569	27	25.20	.07	6.14
145.08	4.18	429	1.70	22.39	1.21	535	28	24.09	.07	5.76
145.99	6.18	430	2.83	32.90	1.28	532	20	35.73	.08	5.78
146.76	3.61	431	1.54	21.42	1.08	593	29	22.96	.07	6.36
147.52	5.43	431	2.23	30.36	1.16	559	21	32.59	.07	6.00
147.99	4.53	430	2.34	23.96	1.19	528	26	26.30	.09	5.80
148.84	4.22	425	2.16	26.69	0.56	632	13	28.85	.07	6.83
149.19	4.19	431	1.77	22.75	0.92	542	21	24.52	.07	5.85

Depth	TOC	Tmax	S1	S2	S3	HI	OI	S1+S2	PI	Ratio
m	%	°C		mg/g				kg/t		kg/t /%TOC
Rodgers WB-1, Drummond Island										
117.50	7.38	427	3.19	38.46	1.44	521	19	41.65	.08	5.64
117.65	4.45	432	1.85	25.47	1.08	572	24	27.32	.07	6.13
118.56	4.87	430	2.01	26.91	1.15	552	23	28.92	.07	5.93
118.68	6.11	431	2.75	33.89	1.05	554	17	36.64	.08	5.99
119.17	10.34	430	5.10	55.00	1.59	531	15	60.10	.08	5.81
120.09	6.64	427	2.42	33.59	1.47	505	22	36.01	.07	5.42
121.06	6.44	430	3.04	35.71	1.29	554	20	38.75	.08	6.17
122.52	4.43	429	1.74	24.33	1.16	549	26	26.07	.07	5.88
123.29	4.23	432	1.85	25.47	1.15	602	27	27.32	.07	6.45
124.20	4.55	429	1.89	25.95	1.29	570	28	27.84	.07	6.11
124.96	3.56	433	1.59	20.16	1.22	566	34	21.75	.07	6.10
128.27	4.93	434	1.95	26.78	1.32	543	26	28.73	.07	5.82
Rodgers WB-2, Drummond Island										
229.88	6.88	439	3.58	33.87	0.72	492	10	37.25	.10	5.41
230.97	4.29	439	1.75	20.96	0.64	488	14	22.71	.08	5.29
231.73	4.52	435	2.70	20.56	0.83	454	18	23.26	.12	5.14
232.92	6.30	439	2.94	30.08	0.69	477	10	33.02	.09	5.24
233.84	5.33	438	2.78	26.97	0.67	506	12	29.75	.09	5.58
234.84	3.72	438	2.03	16.93	0.65	455	17	18.96	.11	5.33
235.54	6.76	439	3.43	35.61	0.82	526	12	39.04	.09	5.78
236.22	4.99	437	2.56	24.07	0.77	482	15	26.63	.10	5.33
236.89	7.28	436	3.51	40.08	0.89	550	10	43.59	.08	5.98
OGS 85-7, Cockburn Island										
324.87	7.32	430	3.21	38.75	1.13	529	15	41.96	.08	5.73
325.12	2.57	435	2.68	9.29	0.76	361	29	11.97	.22	4.65
325.36	3.05	434	2.51	10.77	0.93	353	30	13.28	.19	4.35
325.85	2.44	435	2.64	10.06	0.79	412	32	12.70	.21	5.20
326.20	5.50	436	4.51	26.64	0.43	484	7	31.15	.14	5.66
326.62	3.79	434	3.27	15.99	0.93	421	24	19.26	.17	5.08
327.10	3.02	437	1.74	12.93	0.74	428	24	14.67	.12	4.85
327.72	5.46	440	2.63	27.46	0.67	502	12	30.09	.09	5.51
328.30	10.48	438	4.54	47.92	0.81	457	7	52.46	.09	5.00
328.94	9.04	440	4.08	44.73	0.75	494	8	48.81	.08	5.39
329.84	4.77	441	1.82	24.01	0.70	503	14	25.83	.07	5.41
330.73	4.32	440	1.72	21.78	0.61	504	14	23.50	.07	5.43
331.08	3.69	439	1.52	18.92	0.60	512	16	20.44	.07	5.53
331.40	5.37	438	2.14	27.88	0.69	519	12	30.02	.07	5.59
331.56	4.27	438	1.36	20.86	0.59	488	13	22.22	.06	5.20
OGS SIS 07, Manitoulin Island										
#19.7	5.08	439	1.24	17.97	1.04	355	20	19.21	.06	3.78
*19.81	7.33	440	2.17	30.42	0.92	415	12	32.59	.06	4.44
*21.34	5.94	441	1.68	26.72	0.82	449	13	28.40	.05	4.78

Depth	TOC	Tmax	S1	S2	S3	HI	OI	S1+S2	PI	Ratio
m	%	°C		mg/g				kg/t		kg/t /%TOC
OGS 83-5 Little Current, Manitoulin Island										
109.18	5.25	436	2.18	28.44	0.69	541	13	30.52	.07	5.80
109.89	5.32	437	2.05	28.26	0.75	531	14	30.31	.07	5.69
110.44	3.31	439	1.27	17.66	0.61	533	18	18.93	.07	5.71
110.91	4.23	438	2.30	22.90	0.29	541	6	25.20	.09	5.96
111.34	2.94	441	0.99	15.26	0.63	519	21	16.25	.06	5.52
112.12	5.09	438	1.85	25.76	0.85	506	16	27.61	.07	5.42
112.36	4.64	439	1.81	24.05	0.87	518	18	25.91	.07	5.58
112.90	5.70	436	2.39	29.46	1.11	516	19	31.85	.08	5.58
OGS SIS 05, Manitoulin Island										
^16.63	8.0	440	3,90	48.45	1.03	636	13	52.35	.07	6.54
^16.76	7.4	435	4.16	44.80	1.26	605	17	48.96	.08	6.62
*16.76	7.44	436	3.20	32.92	1.69	442	22	36.12	.08	4.85
^17.69	8.0	437	3.94	48.50	1.12	636	14	52.44	.07	6.56
^18.29	4.1	439	1.72	20.01	0.66	488	16	21.73	.07	5.30
^19.81	4.2	439	1.93	20.35	0.66	485	16	22.28	.08	5.30
^20.09	4.2	442	2.20	28.08	0.84	669	20	30.28	.07	7.21
^20.93	4.8	442	2.27	30.64	0.94	638	20	32.91	.06	6.86
^21.13	4.1	438	2.05	24.42	0.76	596	19	26.47	.07	6.46
OGS SIS 06, Manitoulin Island										
^41.99	6.0	441	3.09	34.69	0.91	578	15	37.78	.08	6.30
*42.00m	5.99	439	2.85	28.50	0.81	475	13	31.35	.09	5.23
*42.08m	7.25	440	2.64	37.16	1.74	512	24	39.80	.06	5.48
^42.15	8.0	440	3.43	43.59	1.10	507	14	47.02	.07	5.88
^42.50	7.6	440	3.38	41.06	1.02	540	13	44.44	.07	5.85
*42.50m	7.22	438	2.62	35.00	1.65	484	22	37.62	.06	5.21
^42.64	8.6	442	3.52	43.12	1.06	524	12	46.64	.07	5.42
*42.64m	8.31	437	3.46	38.51	1.44	427	17	38.97	.08	4.68
*42.67	7.19	441	1.89	41.35	1.65	575	22	43.24	.04	6.01
^43.08	9.0	441	3.48	45.44	1.10	505	12	48.92	.07	5.44
*43.08m	7.49	438	2.99	40.36	1.25	538	16	43.35	.06	5.78
^43.38	6.9	441	2.73	36.99	1.08	536	16	39.72	.06	5.76
*43.38m	7.32	440	2.08	30.23	1.60	412	21	32.31	.06	4.41
^43.70	6.3	440	1.91	29.46	1.13	468	18	31.37	.06	4.98
*43.70m	5.50	440	1.60	23.54	1.08	428	19	25.14	.06	4.57
^44.00	4.6	443	1.88	28.71	0.74	624	16	30.59	.06	6.85
*44.00m	4.91	439	1.34	21.25	0.82	432	16	22.59	.05	4.60
^44.20	6.6	440	2.40	34.94	1.32	529	20	37.34	.06	5.66
^44.33	6.8	442	2.32	36.63	0.86	534	13	38.95	.05	5.73
*44.33m	5.87	438	1.82	27.78	1.19	473	20	29.60	.06	5.04
^44.54	5.4	442	1.52	27.80	0.72	515	13	29.32	.05	5.43
^44.87	4.2	443	1.53	25.77	0.66	614	16	27.20	.05	6.48
^45.27	3.4	444	1.27	20.92	0.73	615	21	22.19	.05	6.53
^45.48	4.2	440	1.50	22.58	0.63	538	15	24.08	.06	5.73
^45.70	3.4	441	1.00	16.25	0.61	478	18	17.25	.05	5.07
^45.72	3.6	441	1.17	17.23	0.86	479	24	19.40	.06	5.11
^45.94	3.2	441	1.15	19.62	0.47	613	15	20.77	,05	6.49
^46.17	5.3	443	1.95	35.87	0.90	677	17	37.72	.05	7.12

Depth	TOC	Tmax	S1	S2	S3	HI	OI	S1+S2	PI	Ratio
m	%	°C		mg/g				kg/t		kg/t /%TOC
SIS 06 continued										
*46.17m	4.85	442	1.67	29.50	0.92	608	18	31.17	.05	6.42
^46.45	2.9	441	1.00	16.47	0.57	568	20	17.47	.05	6.02
^46.89	4.8	441	1.78	28.58	0.83	595	17	30.36	.05	6.33
*46.89m	5.42	438	1.57	24.71	0.70	485	12	26.28	.05	4.84
^47.01	2.5	443	0.53	7.63	0.49	305	20	8.16	.06	3.26
^47.24	5.2	441	1.76	25.55	0.93	491	18	27.31	.06	5.25
Quarry, Manitoulin Island										
OS24	5.10	438	2.18	26.69	0.00	523	0	28.87	.08	5.66
OS38	10.00	437	3.58	43.40	0.00	434	0	46.98	.08	4.70
OS41	3.58	438	1.13	14.93	0.00	417	0	16.31	.07	4.55
OGS Clgd 01, Collingwood area										
^52.31	3.1	437	1.20	6.24	0.49	201	16	7.44	.16	2.40
^52.41	3.3	438	1.21	8.32	0.51	252	15	9.53	.12	2.88
^52.51	4.2	436	1.93	18.49	0.62	440	15	20.42	.09	4.86
*52.61m	5.27	436	2.90	36.32	1.02	689	19	39.22	.07	7.43
*52.75m	7.04	438	3.29	41.44	1.27	588	18	44.73	.07	6.35
^52.88	6.9	438	2.47	37.14	0.80	538	12	39.61	.06	5.74
^52.98	7.2	438	2.76	38.64	0.80	537	11	41.40	.06	5.75
*52.98m	5.84	437	2.78	35.12	0.98	601	16	37.90	.07	6.48
*53.19	6.36	434	2.69	34.96	1.41	549	22	37.65	.07	6.29
^53.39		438	2.21	32.13	0.80			34.34	.06	
*53.39m	4.46	435	2.05	26.08	1.28	584	28	28.83	.07	6.30
*53.49m	3.76	436	1.74	23.43	0.77	623	20	25.17	.06	6.69
^53.59	5.5	438	1.87	27.18	0.82	434	15	29.05	.06	5.28
*53.59m	4.17	436	1.77	23.51	0.82	563	19	25.28	.07	6.06
^53.69	3.7	439	1.27	19.93	0.57	539	15	21.20	.05	5.73
^53.79	4.8	438	1.85	30.07	0.67	626	12	31.92	.05	6.65
*53.79m	4.38	435	1.73	24.38	0.81	556	18	26.11	.06	5.96
^53.89	3.3	438	1.10	20.02	0.66	607	23	21.12	.05	6.40
*53.99m	4.47	437	1.91	27.66	0.77	618	17	29.57	.06	6.61
^54.19	2.9	440	1.06	17.60	0.47	607	16	18.66	.05	6.43
*54.86	5.12	438	2.10	34.11	1.46	666	28	36.21	.05	7.07
OGS Clgd 02, Collingwood area										
106.85	2.00	432	1.56	9.95	0.90	497	25	10.45	.14	5.25
107.29	7.50	432	3.38	37.91	3.41	500	13	41.29	.08	5.50
107.60	8.24	435	3.61	42.58	0.98	516	11	46.19	.08	5.60
108.07	8.30	434	3.96	42.93	1.19	517	14	46.89	.08	5.64
108.35	6.14	435	3.06	32.96	0.93	536	15	36.02	.08	5.86
OGS Clgd 03, Collingwood area										
#53.2	10.90	437	3.70	51.36	2.07	476	19	55.06	.06	5.05
#53.4	5.16	435	1.70	17.60	0.54	341	10	19.30	.08	3.74
#53.9	7.05	438	2.22	32.12	2.94	451	41	34.34	.06	4.87
#54.3	5.88	436	1.84	27.15	2.20	458	37	28.99	.06	4.93

Depth m	TOC %	Tmax °C	S1	S2 mg/g	S3	HI	OI	S1+S2 kg/t	PI	Ratio kg/t /%TOC
OGS Clgd 4B, Collingwood area										
^46.80	6.0	437	2.40	32.48	1,24	541	21	34.88	.06	5.81
^47.10	4.3	437	1.78	22.31	1.11	519	25	24.09	.07	5.60
*47.40m	5.38	436	2.12	29.27	1.04	544	19	31.34	.06	5.89
^47.50	6.6	436	3.07	38.62	1.27	585	19	41.69	.07	6.32
*47.67m	4.73	437	2.12	27.58	1.20	585	25	29.70	.07	6.27
^47.83	6.9	435	3.17	38.36	1.49	556	22	41.53	.07	6.02
^48.22	7.4	440	3.17	45.21	1.15	611	16	48.38	.06	6.54
*48.22m	6.26	434	2.76	35.66	1.16	569	18	38.42	.07	6.13
^48.32	6.8	437	2.94	36.56	1.56	538	23	39.50	.07	5.81
OGS Clgd 06A, Collingwood area										
43.58	10.65	440	5.77	55.44	1.04	520	9	61.21	.09	5.74
43.96	5.57	441	2.42	30.56	0.71	548	12	32.98	.07	5.92
44.25	5.81	438	2.68	30.92	0.67	532	11	33.60	.08	5.78
44.63	4.68	443	2.10	26.92	0.61	575	13	28.02	.07	5.98
45.04	4.84	442	3.02	26.48	0.77	547	15	29.50	.10	6.09
OGS Clgd 07A, Collingwood area										
#72.7	4.38	438	1.41	18.09	0.65	413	14	19.50	.07	4.45
#73.1	6.80	438	2.28	32.85	1.83	483	26	35.13	.06	5.16
#73.8	6.05	441	1.84	26.36	1.89	436	31	28.40	.06	4.69
#74.4	6.42	438	2.20	29.61	1.82	461	28	31.81	.06	4.95
Shore-line exposures, Collingwood area										
OS8-F	10.82	436	5.35	54.32	0.10	502	0	59.67	.09	5.51
OS4-A	8.46	435	4.00	46.31	0.69	547	8	50.31	.08	4.55
OS7-A		438	0.07	0.03	1.39			0.10	.70	
OGS SIS 01, Whitby area										
^42.09	5.6	439	3.68	10.63	0.88	190	16	14.01	.26	2.50
^42.99		439	3.63	11.81	0.97			15.44	.23	
^43.31	4.4	442	3.99	12.03	0.80	273	18	16.02	.24	3.64
^43.91	4.1	442	2.70	13.01	1.18	244	29	15.71	.17	3.83
^44.32	3.2	439	2.77	10.51	1.27	328	40	13.28	.20	4.15
^44.72	3.9	446	2.27	12.27	1.03	315	26	14.54	.15	3.73
^45.02	3.5	442	2.29	8.97	1.05	256	30	11.26	.20	3.22
OGS SIS 03, Whitby area										
#32.0	7.62	440	5.63	21.49	0.49	289	6	27.12	.20	3.55
#32.7	3.61	446	2.21	5.25	0.44	144	12	7.41	.28	2.14
#33.1	4.71	444	3.42	11.07	0.55	239	11	14.49	.23	3.07
#33.4	4.13	445	2.34	7.55	0.89	184	21	9.89	.23	2.39
#34.0	5.68	442	1.69	5.42	0.67	95	11	7.11	.23	1.25
#34.8	4.47	444	2.88	10.16	0.58	233	13	13.04	.22	2.01
#34.9	4.54	445	2.42	8.07	1.19	180	26	10.49	.23	2.31

Depth m	TOC %	Tmax °C	S1	S2 mg/g	S3	HI	OI	S1+S2 kg/t	PI	Ratio kg/t /%TOC
OGS SIS 02, Whitby area										
^21.49	4.6	442	2.99	13.47	0.50	293	11	16.46	.18	3.58
^23.01	5.2	440	3.45	13.81	0.90	266	17	16.26	.21	3.13
^24.19	2.9	439	2.24	10.00	0.96	345	33	19.50	.11	6.72
^24.54	4.7	443	2.39	11.25	0.72	233	15	13.64	.17	2.90
Bowmanville Quarry										
BQ-A	2.72	447	2.07	7.77	0.00	350	0	9.84	.21	4.43
BQ-B	0.76	441	0.97	2.58	0.00	339	0	3.55	.27	4.67
BQ-C	0.27	435	0.24	0.45	0.21	166	77	0.69	.33	2.55
BQ-D	1.01	433	0.20	3.06	0.24	302	23	3.26	.06	3.22